Assessment of Residual Stresses on the Fatigue Behavior of Aircraft Structural Joints

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Abstract

The aging aircraft research programs conducted by the Federal Aviation Administration (FAA) [1], NASA [2], and the aircraft industry (see i.e. [3]) have developed methodologies to assess widespread fatigue damage (WFD) in aircraft structural joints. Verification of these methodologies is carried out on laboratory coupons and on flat or curved lap-splice joints. An issue that is still unclear is an understanding of the initial stages of multiple-site damage (MSD) formation and growth. Knowledge of MSD nucleation time and pattern, (i.e. distribution), as well as its subsequent growth, is a prerequisite for planning an acceptable program to preclude the occurrence of WFD. As building block task to understanding MSD initiation, fatigue and small-crack-growth behavior of production-quality and polished holes in 2024-T3 aluminum alloy sheet material were investigated. The studies on laboratory coupons indicated that production-quality holes behave quite differently from polished holes. Production-quality holes produce fatigue lives 5 to 7 times longer than polished holes. From the industry/government studies, laboratory lap-splice joints were also shown to behave quite differently than actual fuselage joints. A laboratory joint may be tight, have residual stresses, and produce interference due to the rivet installation process. Actual aircraft joints do not appear to be as tight and lack significant rivet interference as do laboratory joints [4]. But hole drilling and rivet installation does cause yielding around the rivet hole and the possibility of residual stresses. The acceptance of the life-prediction methodologies with WFD and the transferability of laboratory results to actual flight components hinges on understanding the laboratory results, whether residual stresses are present in the actual joints, and are methods capable of accounting for the residual-stress effects.

In this study, residual stresses will be accounted for in a life-prediction methodology and will be used to evaluate MSD crack initiation and growth and link-up in aircraft structural joints commonly used in fuselages and wings. Computational models will be calibrated and verified using data from coupon, sub-component, and component tests; and data from aircraft destructive evaluation.

Project Objectives

The objective of the present study is to account for residual stresses in a life-prediction methodology in order to evaluate MSD crack initiation and growth and link-up in aircraft structural joints commonly used in fuselages and wings. A building block approach will be used to assess: (1) the influence of residual stresses from machining/drilling on the fatigue behavior of laboratory coupons under both constant-amplitude and flight spectrum loading and (2) the impact of residual stresses from machining/drilling and rivet installation on aircraft structural joints. The material selected is the 2024-T3 aluminum alloy sheet material. Two aircraft manufacturers and a major airline will produce specimens with production-quality holes using different hole-drilling methods. Attempts will be made to measure or to establish the magnitude and distribution of the residual stresses in the production-quality holes. Fatigue tests will be conducted on specimens made of the 2024-T3 material with both production-quality and polished holes.

A three-dimensional weight-function analysis will be developed to calculate the stress-intensity factors for surface and corner cracks at a hole with an arbitrary residual-stress distribution. The weight-function analysis, K3D, will be incorporated into the FASTRAN life-prediction code. Fatigue-life analyses on polished and production-quality holes will be made using small-crack theory and the residual-stress distributions measured or assumed from trial-and-error procedures. The influence of nucleating-particle distributions and residual-stress variations on calculated fatigue lives will be studied. An assessment on the influence of machining residual stresses and rivet installation on the fatigue behavior of aircraft structural joints and its impact on the prediction of widespread fatigue damage will be made.

Research Activities

An aluminum alloy (2024-T3) sheet material was obtained from the NASA Langley Research Center and coupons are being machined. This material is widely used in the aircraft industry and has a well documented fatigue and fatigue-crack growth history. Specimens with production-quality drilled holes will be obtained from several sources (two aircraft manufactures and an airline). Each source will document the drill type, drill speed, and rate of penetration. At least 5 specimens are to be drilled at each set of conditions. Specimens with polished holes (electro-polished or chemically polished) will be also obtained. These specimens will be the control set of specimens without significant machining residual stresses. X-ray diffraction or other methods will be used to measure or establish the residual stresses on the bore of the hole as a function of drilling technique (Georgia Tech or at the Oak Ridge National Laboratory). Constant-amplitude and simple flight spectra (TBD) loading fatigue tests will be conducted on the specimens with both polished and production-quality holes. Single-spike overload tests will be conducted on polished single-edge-notched tension specimens to induce a residual-stress field to help verify the analysis methodology.

Enhance the K3D, weight-function analysis [5], code for calculating stress-intensity factors for surface and corner cracks at holes with arbitrary residual-stress distributions applied to the crack surfaces. Extend the range of the three-dimensional weight-function analyses to cover very deep surface and corner cracks at holes. Finite element analyses, similar to Ref. 7, will be conducted to see how rivet installation affects the residual stress fields. Interface the K3D code with the FASTRAN [6] life-prediction code for conducting fatigue-crack growth analyses. Fatigue life analyses on polished and production-quality holes will be made using small-crack theory and the residual-stress distributions measured or assumed from trial-and-error analyses. The influence of inclusion-particle distributions (previously made on this 2024-T3 alloy) and variability of the residual-stress distributions on fatigue lives will be assessed on typical aircraft joint configurations.

Anticipated Results

(1) Residual stress distributions caused by the hole drilling process in aircraft fuselage material.
(2) Weight-function method to determine stress-intensity factors for surface and corner cracks at hole due to arbitrary residual stress distributions.
(3) Fatigue life results on laboratory coupons under constant-amplitude, variable-amplitude, and spectrum loading using production-quality and polished holes.
(4) Incorporate the weight-function method into a life-prediction code.
(5) Fatigue life analyses, using small-crack theory, initial discontinuity states, and residual-stress distributions, on laboratory coupons under constant-amplitude, variable-amplitude, and spectrum loading using production-quality and polished holes.
(6) Assessment of production-quality lap-splice joint specimens from several sources.
(7) Assessment of the impact of residual stresses on more realistic structural configurations

Accomplishments

(1) Laboratory coupons have been machined from 2024-T3 sheet material at the NASA Langley Research Center.

References

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